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Strangeness and Metastable Neutron Stars: What Might have Happened to SN1987A

Immediately after they are born, neutron stars are characterized by an entropy per baryon of order unity and by the presence of trapped neutrinos. If the only hadrons in the star are nucleons, these effects slightly reduce the maximum mass relative to cold, catalyzed matter. However, if negatively charged particles in the form of hyperons, a kaon condensate, or quarks are also present, these effects result in an increase in the maximum mass of $\sim 0.2\mathrm{M}_\odot$ compared to that of a cold, neutrino-free star. This could lead to the delayed formation of a black hole; such a scenario is consistent with our present knowledge of SN1987A.

Key Words: *Neutron stars, strangeness, delayed black hole formation*

1. A NEUTRON STAR IS BORN

Neutron stars are thought to originate from the core collapse of stars of mass $\gtrsim 8$ solar masses ($\mathrm{M}_\odot$) at the end of their lives. The collapsing core subdivides into an inner region, in which the infall velocity is proportional to the radius, and an outer region, which collapses less quickly. When the central density of the inner core significantly exceeds that of an atomic nucleus, the core bounces. The resulting collision with the still-infalling outer core generates a shock wave. Although the shock wave rapidly moves outwards, it stalls within the outer core at a radius of a few hundred km. Accretion of infalling matter through the shock generates sufficient energy in the form of neutrinos to

support the shock and prevent a recollapse for up to several tenths of a second. Present calculations [1] suggest that convection supplies additional energy which results in a supernova explosion and the expulsion of most of the mass exterior to the core.

Initially, the remnant's gravitational mass is less than 1 $M_\odot$. The remnant, termed the protoneutron star, is lepton rich and has an entropy per baryon of $S \simeq 1$ (in units of Boltzmann's constant k_B). The leptons include both electrons and neutrinos, the latter being trapped in the star because their mean free paths in the dense matter are of order 1 cm, whereas the stellar radius is about 15 km. Accretion onto the neutron star increases its mass to the 1.3–1.5 $M_\odot$ range, and should mostly cease after a second. It then takes about 10–15 s [2] for the trapped neutrinos to diffuse out, and in the diffusion process they leave behind most of their energy, heating the protoneutron star to fairly uniform entropy values of about $S = 2$. Cooling continues as thermally-produced neutrinos diffuse out and are emitted. After about 50 s, the star becomes completely transparent to neutrinos and the neutrino luminosity drops precipitously [3].

The fate of the dense remnant left behind from the explosion depends upon the equation of state (EOS) and the amount of additional material that falls back onto it. General relativity implies that there is a maximum mass for a given equation of state. Observations of PSR 1913+16 [4] and causality [5] limit the maximum mass of cold, catalyzed matter M_{max} to the range 1.443 $M_\odot \lesssim M_{max} \lesssim 3$ $M_\odot$. However, the maximum mass of matter with abundant trapped leptons, M^L_{max}, may be larger or smaller than M_{max}. There are, therefore, two possible ways that a black hole could form after a supernova explosion. First, accretion of sufficient material could increase the remnant's mass to a greater value than either M_{max} or M^L_{max} and produce a black hole, which then appears on the accretion time scale [6]. Second, if accretion is insignificant after a few seconds, and if $M^L_{max} > M > M_{max}$, where M is the final remnant mass, then a black hole will form

as the neutrinos diffuse out [7, 8, 9, 10, 11], on the deleptonization time scale of 10–15 s. This scenario, involving metastable neutron stars, is the topic of this Comment; a recent review is to be found in Ref. [7].

The existence of metastable neutron stars has some interesting implications. First, it could explain why no neutron star is readily apparent in the remnant of SN 1987A despite our knowledge that one existed until at least 12 s after the supernova's explosion. Second, it would suggest that a significant population of relatively low mass black holes exists [12], one of which could be the compact object in the X-ray binary 4U1700-37 [13].

2. STRUCTURE OF NEWBORN NEUTRON STARS

How is the stellar structure, particularly the maximum mass, influenced by the trapped neutrinos? (The finite entropy, as we shall see, plays a lesser role.) In order to investigate this question, one needs the EOS up to ~ 10 times the baryon density encountered in the center of a nucleus. The EOS at such high densities is not known with any certainty. Nevertheless, recent work [14, 15, 16] has emphasized the possibility that hyperons, a condensate of K^- mesons, or u, d, and s quarks, may be present in addition to nucleons and leptons. These additional components can appear separately or in combination with one another. Notice that all of these cases introduce the strange s quark into the neutron star and involve negatively-charged, strongly-interacting particles. Compared to a star containing just plain-vanilla nucleons and leptons, the presence of these additional components qualitatively changes the way in which the structure of the star depends upon neutrino trapping [7]. In particular, they permit the existence of metastable neutron stars, which could collapse to black holes during deleptonization.

The composition of the star is determined by two important physical constraints.

The first is charge neutrality – there must be equal numbers of positively and negatively charged particles at a given density. The second is beta equilibrium – because the time scales of weak interactions, including those of strangeness violating processes, are short compared to the dynamical time scales of evolution, chemical equilibrium is achieved among the various possible constituents. For example, the process $p + e^- \leftrightarrow n + \nu_e$ in equilibrium establishes the relation

$$\mu \equiv \mu_n - \mu_p = \mu_e - \mu_{\nu_e} \,, \tag{1}$$

allowing the proton chemical potential to be expressed in terms of three independent chemical potentials: μ_n, μ_e, and μ_{ν_e}. At densities where μ exceeds the muon mass, muons can be formed by $e^- \leftrightarrow \mu^- + \overline{\nu}_\mu + \nu_e$, hence the muon chemical potential is

$$\mu_\mu = \mu_e - \mu_{\nu_e} + \mu_{\nu_\mu} \,, \tag{2}$$

requiring the specification of an additional chemical potential μ_{ν_μ}. Negatively charged kaons can be formed in the process $n + e^- \leftrightarrow n + K^- + \nu_e$ when $\mu_{K^-} = \mu$ becomes equal to the energy of the lowest eigenstate of a K^- in matter. Weak reactions for the Λ, Σ, and Ξ hyperons are all of the form $B_1 + \ell \leftrightarrow B_2 + \nu_\ell$, where B_1 and B_2 are baryons, ℓ is a lepton, and ν_ℓ a neutrino of the corresponding flavor. The chemical potential for baryon B with baryon number b_B and electric charge q_B is then given by the general relation

$$\mu_B = b_B \mu_n - q_B \mu \,, \tag{3}$$

which leads to

$$\mu_\Lambda = \mu_{\Sigma^0} = \mu_{\Xi^0} = \mu_n \quad ; \quad \mu_{\Sigma^-} = \mu_{\Xi^-} = \mu_n + \mu \quad ; \quad \mu_p = \mu_{\Sigma^+} = \mu_n - \mu \,. \tag{4}$$

Applied to matter containing quarks, Eq. (3) gives

$$\mu_d = \mu_s = (\mu_n + \mu)/3 \quad ; \quad \mu_u = (\mu_n - 2\mu)/3 \,. \tag{5}$$

If there are no trapped neutrinos present, so that $\mu_{\nu_\ell} = 0$, there are two independent chemical potentials (μ_n, μ_e) representing conservation of baryon number and charge. If trapped neutrinos are present $(\mu_{\nu_\ell} \neq 0)$ further constraints, due to conservation of the various lepton numbers over the dynamical time scale of evolution, must be specified. Defining the concentrations $Y_i = n_i/n$, where the density of species i is n_i and n is the total *baryon* density, the total (electron type) lepton fraction is $Y_\ell = Y_e + Y_{\nu_e}$. At the onset of trapping, during the initial inner core collapse, $Y_\ell \approx 0.4$ and $Y_e/Y_{\nu_e} \sim 5-7$ depending upon the density [17]. These numbers are not significantly affected by variations in the EOS. Following deleptonization, $Y_{\nu_e} = 0$, and Y_e can vary widely, both with density and with the EOS.

In the case of muons it is generally true that, unless $\mu > m_\mu c^2$, the net number of μ's or ν_μ's present is zero. Because no muon-flavor leptons are present at the onset of trapping, $Y_{\nu_\mu} = -Y_\mu$. Following deleptonization, $Y_{\nu_\mu} = 0$, and Y_μ is determined by $\mu_\mu = \mu_e$ for $\mu_e > m_\mu c^2$ and is zero otherwise.

As long as both weak and strong interactions are in equilibrium, the above general relationships determine the constituents of the star during its evolution. Since electromagnetic interactions give negligible contributions, it is sufficient to consider the non-interacting (Fermi gas) forms for the partition functions of the leptons. Hadrons, on the other hand, receive significant contributions at high density from the less well known strong interactions.

To present specific results, we employ a relativistic field theoretical model in which the baryons, B, interact via the exchange of σ, ρ, and ω mesons. The meson fields are determined by extremization of the partition function. The purpose of the $\sigma(\sim 550\ 0^+,\ T = 0)$ meson is to simulate the attractive effect of two pion exchange, while the $\omega(782\ 1^-\ T = 0)$ provides short range repulsion, and the $\rho(770\ 1^-\ T = 1)$ accounts

for the isospin dependence of the interaction (the loss of attraction when the number of neutrons and protons differs). In the case in which only nucleons are considered, $B = n, p$, this is the well-known Walecka model [18]. The nucleon coupling constants are chosen to reproduce the binding energy ($\sim$ 16 MeV), symmetry energy ($\sim 30 - 35$ MeV), equilibrium density ($n_0 = 0.16 \pm 0.01$ fm^{-3}), compression modulus (200 MeV $\lesssim K_0$ $\lesssim$ 300 MeV), and nucleon Dirac effective mass $(0.6 - 0.7) \times 939$ MeV of infinite nuclear matter. The compression modulus and the effective mass influence the stiffness of the high density EOS and M_{max}.

We turn now to the cases in which strange particles are allowed. In the first model [14], we augment the set of baryons B to include the Λ, Σ, and Ξ hyperons. The hyperon-meson coupling constants are not well known, but we can take some guidance from hypernuclear data. For example, in nuclear matter at saturation, the lowest Λ level is bound by 28 MeV. This establishes a correlation between the σ and ω couplings [19]. Fits to Λ-hypernuclear levels constrain the range over which these couplings may be varied to obtain satisfactory neutron star properties. The ρ-coupling is of less consequence and may be taken to be of similar order. The Σ^- atom analysis of Mareš *et al.* [20] offers some guidance on the Σ^- couplings, which are of similar magnitude to those of the Λ. Unfortunately, very little is known about the Ξ couplings from data; hence, we assume them to be of similar magnitude to those of the Λ and Σ^-.

In the second model, we allow for kaons in addition to nucleons and leptons. The kaon-nucleon interaction may also be generated by the exchange of σ, ρ, and ω mesons [21]. The qualitative results of kaon condensation in this meson exchange model are similar to those of the chiral model of Kaplan and Nelson [15] when the magnitudes of the kaon-baryon interactions in the two models are required to yield compatible kaon optical potentials in nuclear matter. Friedman *et al.* [22] have recently suggested a strongly attractive K^-

optical potential of depth -200 ± 20 MeV for best fits to kaonic atom data. Theoretically, the major uncertainty lies in value of the kaon-nucleon sigma term, Σ^{KN}, which depends on the strangeness content of the proton. For present purposes, we take $\Sigma^{KN} = 344$ MeV on the basis of recent lattice gauge simulations [23].

Fig. 1 shows the various concentrations as a function of density when the only hadrons present are nucleons; here, the arrows indicate the central density of the maximum mass stars. The left hand panel refers to the case in which the neutrinos have left the star. At high density the proton concentration is about 30%, charge neutrality ensuring an equal number of negatively charged leptons. This relatively large value is the result of the symmetry energy increasing nearly linearly with density in this model. Many non-relativistic potential models [24] predict a maximum proton concentration of 10%. The effects of neutrino trapping are displayed in the right hand panel. The fact that $\mu_{\nu_e} \neq 0$ in Eq. (1) results in larger values for μ_e and Y_e. Because of charge neutrality, Y_p is also larger, and it approaches 40% at high density. As is evident from the third column of Table I, neutrino-trapping reduces the maximum mass M^L_{max} from the value found in neutrino-free matter M_{max}; although neutrino-trapped nucleons-only matter contains more leptons and more leptonic pressure, it also contains more protons and, therefore, less baryonic pressure. It is also evident from the table that thermal effects increase the pressure and therefore the maximum mass, but only slightly. Even for $S = 2$, the central temperature is only ~ 50 MeV, which is much less than the nucleon Fermi energies. Thus, in the absence of significant accretion at late times, a black hole could only form promptly after bounce from nucleons-only stars, because $M^L_{max} \lesssim M_{max}$.

Fig. 2 is the analogue of Fig. 1 for the case in which hyperons are allowed to be present. In the neutrino free case (left-hand panel), the $\Lambda(1116)$ and the $\Sigma^-(1197)$ appear at roughly the same density because the somewhat higher mass of the Σ^- is compensated

by the presence of the electron chemical potential in the chemical equilibrium condition, Eq. (4). More massive, and more positively charged, particles than these appear at higher densities. Following the appearance of the negatively charged Σ^- hyperon the lepton concentrations fall because of charge neutrality. The rapid build-up of the other hyperons with increasing density produces a system which is strangeness-rich at high density and which contains nearly as many protons as neutrons. The introduction of new baryonic species and the lower lepton abundances significantly reduce the pressure. This substantially reduces the maximum mass [14] compared to the nucleons-only case, as seen from column four of Table I.

Table I

Maximum neutron star gravitational masses in solar units with and without trapped neutrinos

		Strange hadrons		
	S	None	Hyperons	Kaons
No trapped neutrinos	0	2.01	1.54	1.83
Trapped neutrinos	0	1.94	1.77	1.93
Trapped neutrinos	2	1.98	1.78	1.97

The entropy/baryon is denoted by S.

In the case in which neutrinos are trapped (right-hand panel of Fig. 2) the threshold for the appearance of the Σ^- is significantly raised, since $\mu = \mu_e - \mu_{\nu_e}$ is much smaller than μ_e in the untrapped case. Furthermore, the abundances of all hyperons are smaller,

owing to the larger number of electrons. These effects stiffen the EOS compared to the neutrino free case. Thus, in Table I, M^L_{max} is $\sim 0.2\mathrm{M}_\odot$ larger than M_{max}, exactly the opposite behavior to that obtained in the absence of strange particles.

Fig. 3 shows the effect of kaon condensation. We see that in the neutrino-free case (left panel) the attractive interaction between K^- mesons and nucleons allows a condensate to form at a density of $3.6n_0$. Beyond this density the proton concentration increases dramatically, balanced by a roughly equal number of kaons, and at large densities it becomes almost equal to the neutron concentration. The EOS is thus softened, and the maximum mass reduced relative to the nucleons-only case (see column five of Table I), although by a lesser amount than for hyperons with the models displayed here. When neutrinos are trapped (right panel) the K^- threshold is raised and, given the density for a maximum mass star (arrow), it is clear that the condensate plays a much lesser role. Thus the EOS is stiffer and the maximum mass is raised. The effect is qualitatively similar to that engendered by hyperons. A similar effect is also obtained if u, d, and s quarks are allowed to be present [10].

Evolutionary calculations [2, 9] without accretion show that it takes on the order of 10–15 seconds for the trapped neutrino fraction to vanish for a nucleons-only EOS. In the absence of black hole formation, this evolution should be qualitatively independent of the EOS [7]. This is roughly borne out in the calculations of Keil and Janka [9]. Fig. 4 shows the dependence of the maximum stellar mass upon Y_{ν_e}. When the only hadrons are nucleons (np) the maximum mass increases with Y_{ν_e}, whereas when hyperons (npH) or kaons (npK) are also present, it decreases. Further, the rate of decrease accelerates for rather small values of Y_{ν_e} . The implication is clear. *If* hyperons, kaons, or other negatively-charged hadronic species are present, an initially stable star can change into a black hole after most of the trapped neutrinos have left, and this takes $10-15$ s. This

happens if the remnant mass M satisfies $M^L_{max} > M > M_{max}$.

3. SUPERNOVA SN1987A

On February 23 of 1987, neutrinos were observed [25] from the explosion of supernova SN1987A, indicating that a neutron star, not a black hole, was initially present. (The appearance of a black hole would have caused an abrupt cessation of any neutrino signal [3].) The neutrino signal was observed for a period of at least 12 s, after which counting statistics fell below measurable limits. From the handful of events observed only the average neutrino energy, $\sim$ 10 MeV, and the total binding energy release of $\sim (0.1 - 0.2)\mathrm{M}_\odot$ could be estimated.

These estimates, however, do not shed much light on the composition of the neutron star. This is because, to lowest order, the average neutrino energy is fixed by the neutrino mean free path in the outer regions of the protoneutron star. Further, the binding energy exhibits a universal relationship [7] for a wide class of EOSs, including those with strangeness bearing components, namely

$$B.E. = (0.065 \pm 0.01)(M_B/\mathrm{M}_\odot)^2 \mathrm{M}_\odot \,, \tag{6}$$

where M_B is the baryonic mass. This allows us only to determine a remnant gravitational mass of $(1.14 - 1.55)\mathrm{M}_\odot$, but not the composition.

The ever-decreasing optical luminosity (light curve) [26] of the remnant of SN1987A suggests two arguments against the continued presence of a neutron star. First, accretion onto a neutron star at the Eddington limit is already ruled out for the usual hydrogen-dominated Thomson electron scattering opacity. (However, if the atmosphere surrounding the remnant contains a sufficient amount of iron-like elements, as Chen and Colgate [27]

suggest, the appropriate Eddington limit is much lower.) Second, a Crab-like pulsar cannot exist in SN1987A, since the emitted magnetic dipole radiation would be observed in the light curve. Either the magnetic field or the spin rate of the neutron star remnant would have to be much less than in the case of the Crab, and what is inferred from other young neutron stars. The spin rate of a newly formed neutron star is expected to be high, however the time scale for the generation of a significant magnetic field is not well known and could be greater than 10 years.

Although most of the binding energy is released during the initial accretion and collapse stage in about 2 seconds after bounce, the neutrino signal continued for a period of at least 12 s. The compositionally-induced changes in the structure of the star occur on the deleptonization time scale which we have estimated to be of order 10–15 s [7], not on the binding energy release time scale. Thus, the duration of the neutrino signal from SN1987A was comparable to the time required for the neutrinos initially trapped in the star to leave. However, counting statistics prevented measurement of a longer duration, and this unfortunate happenstance prevents one from distinguishing a model in which negatively-charged matter appears and a black hole forms from a less exotic model in which a neutron star still exists. As we have pointed out, the maximum stable mass drops by as much as $0.2\mathrm{M}_\odot$ when the trapped neutrinos depart if negatively charged particles are present, which could be enough to cause collapse to a black hole.

Observed neutron stars lie in a very small range of gravitational masses. The smallest range that is consistent with all the data [4, 28] runs from $1.34\mathrm{M}_\odot$ to $1.44\mathrm{M}_\odot$, the latter value being the accurate measurement of PSR1913+16. Thielemann *et al.* [29] and Bethe and Brown [30] have estimated the gravitational mass of the remnant of SN1987A to be in the range $(1.40 - 1.56)\mathrm{M}_\odot$, using arguments based on the observed amounts of ejected ^{56}Ni and/or the total explosion energy. This range extends above the largest accurately

known value for a neutron star mass, 1.44 $M_\odot$, so the possibility exists that the neutron star initially produced in SN1987A could be unstable in the cold, deleptonized state. In this case, SN1987A would have become a black hole once it had deleptonized, and no further signal would be expected. Should this scenario be observationally verified, it would provide strong evidence for the appearance of strange matter.

4. FUTURE DIRECTIONS

The emitted neutrinos, of all flavors, are the only direct probe of the mechanism of supernova explosions and the structure of newly formed neutron stars. The cooling of the star can yield information on the stellar composition for which accurate simulations with appropriate neutrino opacities will be necessary. At the same time, further information on the crucial question of the strong interactions of strange particles in dense matter is sorely needed – even near nuclear equilibrium density our knowledge is sketchy at present. This emphasizes the need to pin down the mass shifts of hadrons in dense matter utilizing a reliable many-body description.

What can be expected in future detections? In an optimistic scenario, several thousand neutrinos from a typical galactic supernova might be seen in upgraded neutrino detectors, such as SNO in Canada and Super Kamiokande in Japan. (For rough characteristics of present and future neutrino detectors see Ref. [31].) The coincidence between the deleptonization time scale and the detection time scale that happened in the case of SN1987A will not occur. Among the interesting features that could be sought are:

1. Possible cessation of a neutrino signal due to black hole formation.

2. Possible burst or light curve feature associated with the onset of negatively-charged

strongly interacting matter near the end of deleptonization, whether or not a black hole is formed.

3. Identification of the deleptonization/cooling epochs by changes in luminosity evolution or neutrino flavor distribution.

4. Determination of a radius-mean free path correlation from the luminosity decay time or the onset of neutrino transparency.

5. Determination of the neutron star mass from the universal binding energy-mass relation.

To realize the above goals and to adequately discriminate between the various possibilities, detailed information about the characteristics of neutrino detectors must be made available. This is especially important in deciphering the time evolution of the neutrino signal, even if a large number of neutrinos are detected.

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PAUL J. ELLIS
School of Physics and Astronomy
University of Minnesota
Minneapolis, MN 55455

JAMES M. LATTIMER
Department of Earth and Space Sciences
State University of New York
Stony Brook, NY 11794

MADAPPA PRAKASH
Department of Physics
State University of New York
Stony Brook, NY 11794

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Figure Captions

Fig. 1. Individual concentrations, Y_i, as a function of the baryon density ratio $u = n/n_0$, where n_0 is the density of equilibrium nuclear matter. The arrows indicate the central density of the maximum mass stars. Here nucleons, electrons, and muons are in beta equilibrium at an entropy per baryon $S = 1$. Left panel: neutrino free. Right panel: with trapped neutrinos ($Y_\ell = 0.4$).

Fig. 2. As for Fig.1, but for matter which contains hyperons, as well as nucleons, electrons, and muons.

Fig. 3. As for Fig.1, but for matter which contains a kaon condensate, as well as nucleons, electrons, and muons.

Fig. 4. Maximum neutron star mass as a function of Y_{ν_e} for hadronic matter with only nucleons (np) or with nucleons and hyperons (npH) or kaons (npK).

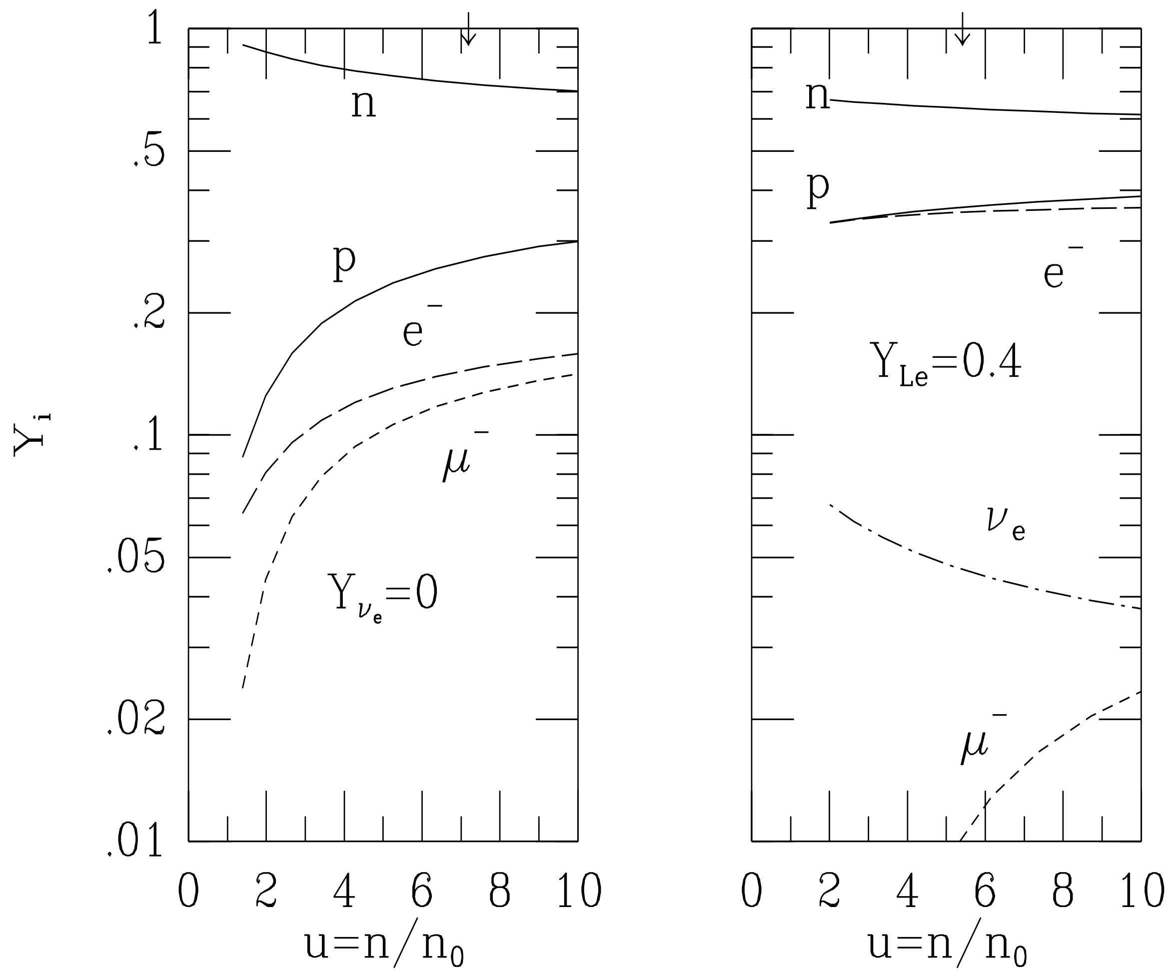
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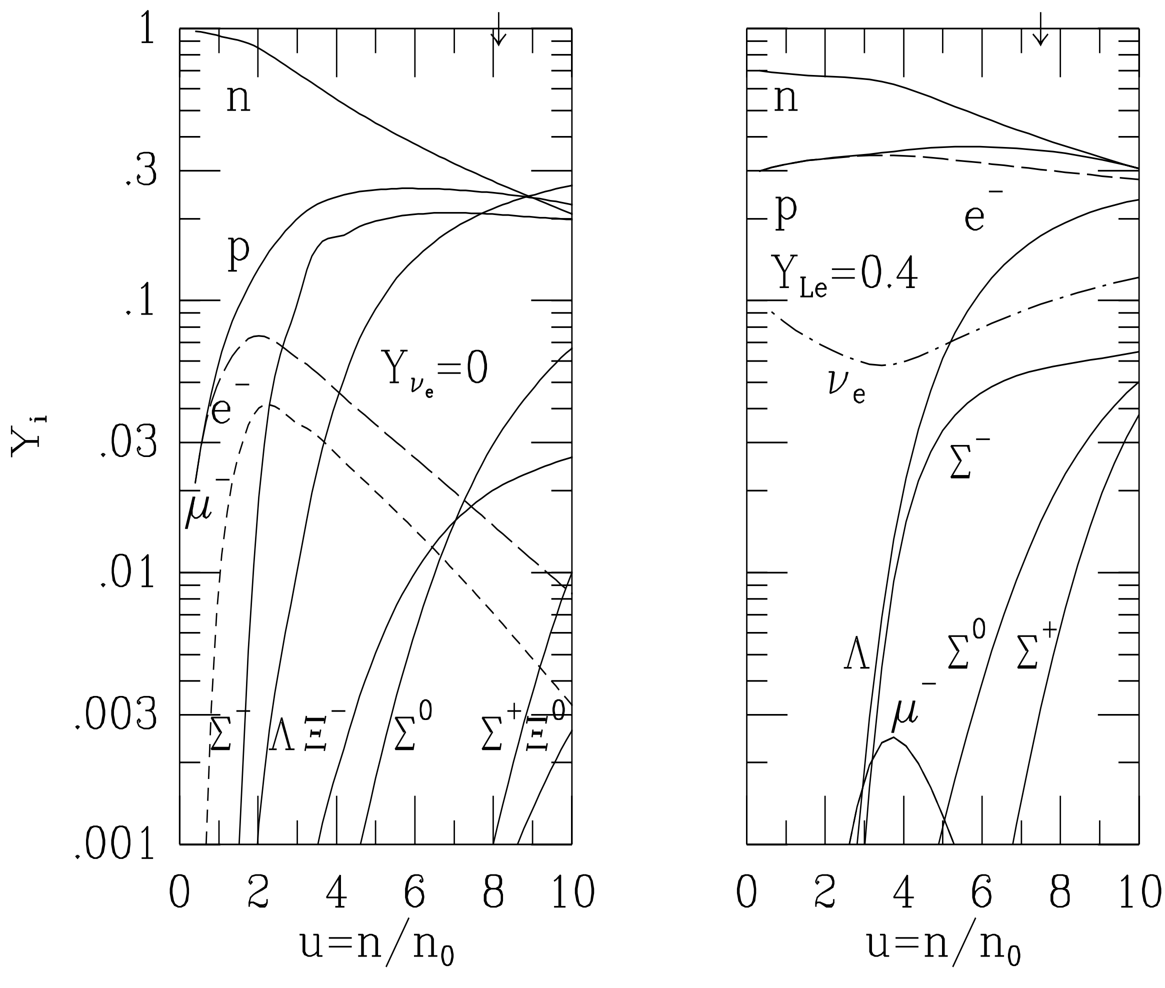
Figure 1:



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$u=n/n_0$
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Figure 2:

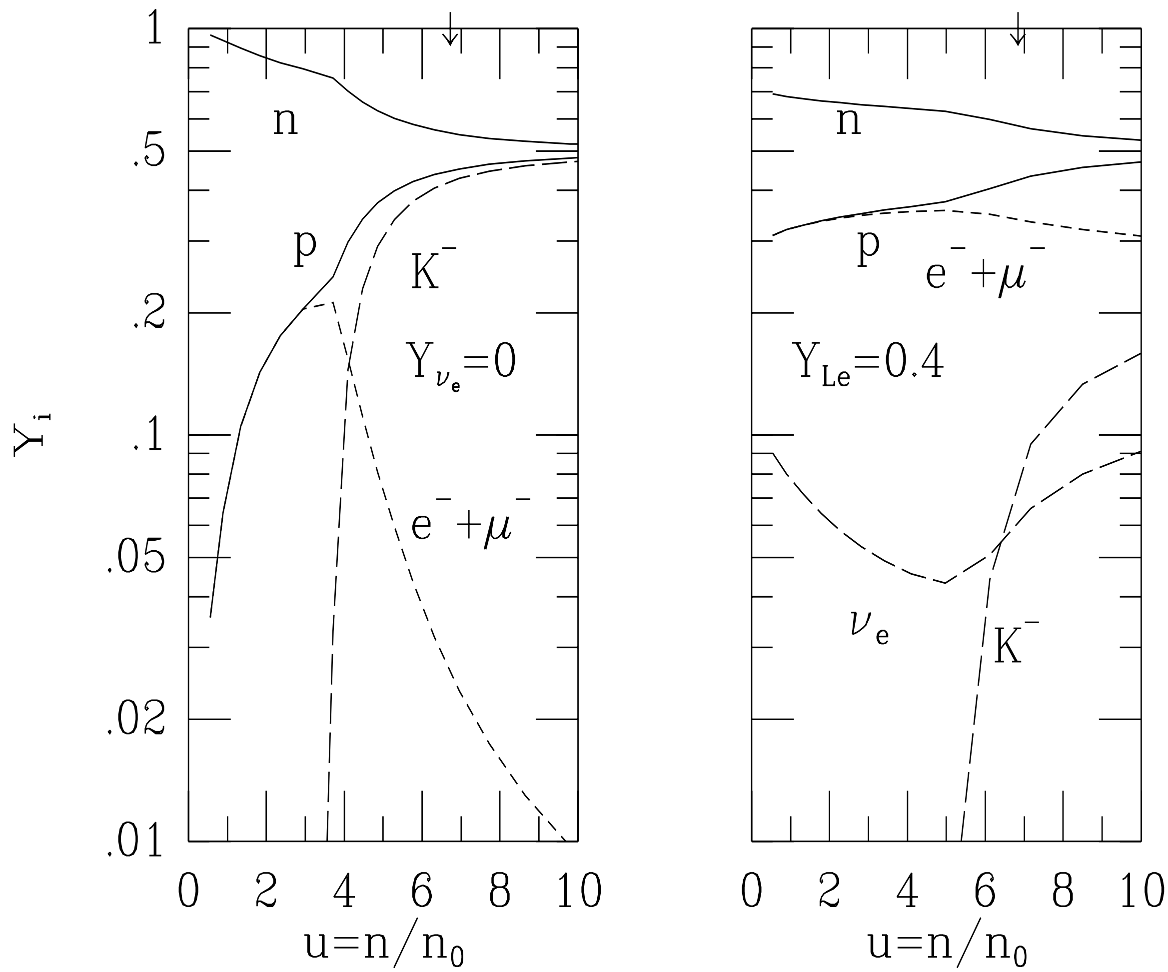

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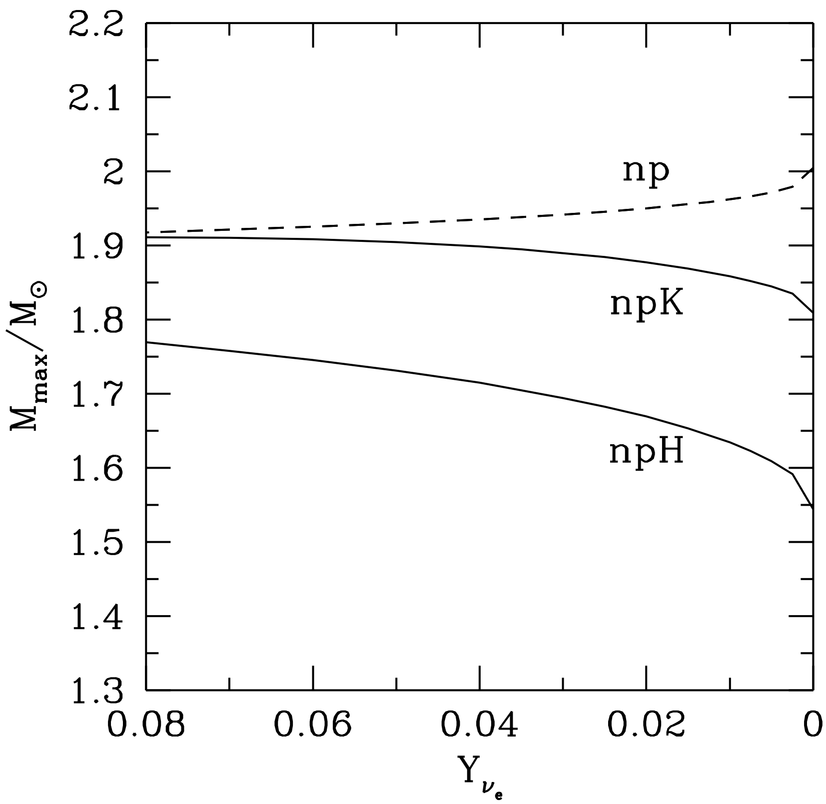
Figure 3:



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2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
0.08
0.06
0.04
0.02
0
np
npK
npH
$M_{max}/M_{\odot}$
Y_{ν_e}

Figure 4: